

# 1. METHODOLOGY

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## 1.1 INTRODUCTION

This chapter provides an overview of the methodology we used to calculate the greenhouse gas (GHG) emissions associated with various management strategies for municipal solid waste (MSW). The chapter begins with a brief discussion of the life cycle framework used for the analysis. Next, it explains how we selected the ten materials that were analyzed. We then describe the specific GHG emissions and emission offsets considered in calculating the net emissions associated with particular waste management options. Finally, the chapter discusses the life cycle stages that we studied to identify the GHG impacts of MSW management options. Succeeding chapters will describe how we analyzed each step in the life cycle.

## 1.2 THE OVERALL FRAMEWORK: A STREAMLINED LIFE CYCLE INVENTORY

Early in our analysis of the GHG benefits of source reduction and recycling, it became clear that comparing source reduction and recycling to other waste management options would clarify where the greatest GHG benefits could be obtained for particular materials in MSW, and help policymakers identify the best options for GHG reductions. We determined that a streamlined application of life cycle assessment would be the best way to make such comparisons.

A full life-cycle assessment (LCA) is an analytical framework for understanding the material inputs, energy inputs, and environmental releases associated with manufacturing, using, and disposing a given material. A full LCA generally consists of four parts: (1) goal definition and scoping, (2) an inventory of the materials and energy used in all stages in the life of a product or process, and an inventory of environmental releases throughout the product lifecycle; (3) an impact assessment that examines potential and actual human health effects related to the use of resources and environmental releases; and (4) an assessment of the change that is needed to bring about environmental improvements in the product or processes.

A full life-cycle assessment is beyond the scope of this analysis. Rather, this report is a streamlined application of a life cycle assessment that is limited to an inventory of the emissions and other environmental impacts related to global warming; we did not assess air, water, or environmental impacts that did not have a direct bearing on climate change. Moreover, we did not attempt, as part of this analysis, to assess human health impacts or environmental improvements needed.<sup>17</sup>

## 1.3 MSW MATERIALS CONSIDERED IN THE STREAMLINED LIFE CYCLE INVENTORY

We made initial rough estimates of the potential for source reduction and recycling of MSW to reduce GHG emissions for the President's Climate Change Action Plan in 1993. However, it was clear that a more rigorous analysis would be needed to determine the GHG emissions associated with source reduction and recycling and to identify which materials in MSW were most likely to reduce GHG emissions if source reduced or recycled.

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<sup>17</sup> Note that EPA's Office of Research and Development (ORD) is in the early stages of performing a more extensive life cycle inventory for various waste management options for MSW. ORD's analysis is inventorying all emissions (air, water, and waste) associated with these options.

Each material in MSW has different GHG impacts depending on how it is made and disposed. To determine which materials in MSW had the greatest potential to reduce GHG emissions if source reduced or recycled, we performed a screening analysis of 37 of the most common materials and products found in MSW. The screening analysis compared: (1) the GHG emissions from manufacturing each of the 37 materials from virgin or recycled inputs (based on the process and transportation energy requirements, and fuel mix for each material); and (2) the projected source reduction and recycling rates for each material. The information on energy requirements, fuel mix, and recycling rates was estimated independently by two groups with experience in MSW and life cycle assessment: Franklin Associates, Ltd. and the Tellus Institute. Then, ICF Incorporated ranked the materials by their potential for GHG reductions: for each material, ICF (1) averaged the two estimates for energy requirements and fuel mix, then (2) used those averages, together with estimates of the GHG emissions per unit of fuel used, to estimate GHG reductions per ton of product source reduced or recycled, and finally (3) used the estimated GHG reductions per ton, together with the averaged estimates of the potential tonnage of source reduction and recycling, to estimate the total GHG reduction potential for each material.

While the screening analysis was general in nature and employed many assumptions, the underlying data provided by Franklin Associates and the Tellus Institute overlapped a great deal. The energy and recycling data provided by both groups indicated that the same eight manufactured materials had the greatest potential to reduce GHG emissions if they were source reduced or recycled. We chose to limit the life cycle assessment to these eight materials:

- newspaper,
- office paper,<sup>18</sup>
- corrugated cardboard,
- aluminum cans,
- steel cans,
- HDPE (high density polyethylene) plastic,
- LDPE (low density polyethylene) plastic, and
- PET (polyethylene terephthalate) plastic.<sup>19</sup>

To round out the analysis, we also examined the GHG implications of various management strategies for food waste, yard trimmings, and mixed MSW.

#### **1.4 KEY INPUTS AND BASELINES FOR THE STREAMLINED LIFE CYCLE INVENTORY**

Evaluating the GHG emissions of waste management requires analysis of three factors: 1) GHG emissions throughout the life cycle of the material (including the chosen disposal option); 2) the extent to which carbon sinks are affected by manufacturing and disposing the material; and 3) the extent to which the management option recovers energy that can be used to replace electric utility energy, thus reducing utility GHG emissions. In addition, a baseline year must be selected so that changes may be measured in comparison to conditions in that baseline year. Each of these factors warrants further discussion.

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<sup>18</sup> Office paper refers to the type of paper used in computer printers and photocopiers.

<sup>19</sup> Glass was not included in the analysis, partly because of the relatively small difference between the amount of energy used in manufacturing glass from virgin versus recycled inputs.

#### GHGs Emissions Relevant to Waste:

The most important GHGs for purposes of analyzing MSW management options are carbon dioxide, methane, nitrous oxide, and perfluorocarbons. Of these, carbon dioxide (CO<sub>2</sub>) is by far the most common GHG emitted in the US. Most carbon dioxide emissions result from energy use, particularly fossil fuel combustion. A great deal of energy is consumed when a product is made and then thrown away. This energy is used in the following stages: 1) extracting and processing raw materials; 2) manufacturing products; 3) managing products at the end of their useful lives; and 4) transporting materials and products between each stage of their life cycles. We estimated energy-related GHG emissions at all of these stages, except for transportation of products to consumers (because GHG emissions from transportation to consumers will vary little among the options considered). Much of this report is devoted to explaining how we quantified the energy used and the resulting carbon dioxide emissions at each stage in the life cycle of any given material in MSW. Energy consumed in connection with consumer use of products is not evaluated, because energy use for the selected materials is small (or zero) at this point in the life cycle, and in any case, the energy consumed during use would be about the same whether the product was made from virgin or recycled inputs.

Methane (CH<sub>4</sub>), a more potent GHG, is produced when organic waste decomposes in an oxygen-free (anaerobic) environment, such as a landfill. Methane from landfills is the largest source of methane in the US;<sup>20</sup> these emissions are addressed in Chapter 7.

Nitrous oxide (N<sub>2</sub>O), another GHG, results from the use of commercial and organic fertilizers and fossil fuel combustion, as well as other sources. For this analysis, we estimated nitrous oxide emissions from waste combustion.

#### **Comparing GHGs**

Carbon dioxide, methane, and nitrous oxide are very different gases when it comes to their heat-trapping potential. An international protocol has established carbon dioxide as the reference gas for measurement of heat-trapping potential (also known as global warming potential). By definition, the global warming potential of one kilogram (kg) of carbon dioxide is 1.

Methane, which has a much higher heat-trapping capacity, has a global warming potential of 24.5. This means that one kg of methane has the same heat-trapping potential as 24.5 kg of CO<sub>2</sub>.

Nitrous oxide, a more potent GHG, has a global warming potential of 270.

Perfluorocarbons have extremely high global warming potentials: 6,300 for CF<sub>4</sub> and 12,500 for C<sub>2</sub>F<sub>6</sub>.

In this report, emissions of carbon dioxide, methane, nitrous oxide, and perfluorocarbons have been converted to their "carbon equivalents." Because CO<sub>2</sub> is 12/44 carbon by weight, one metric ton of CO<sub>2</sub> is defined as 12/44 or 0.27 metric tons of carbon equivalent (MTCE). The MTCE value for one metric ton of each of the other gases is determined by multiplying its global warming potential by a factor of 12/44. (All data provided here are from US EPA, *Inventory of US Greenhouse Gas Emissions and Sinks: 1990-1994*, November 1995, p. 3.)

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<sup>20</sup> U.S. EPA, *Inventory of US Greenhouse Gas Emissions and Sinks: 1990-1994*, EPA 230-R-96-006, November 1995, p. ES-10.

Perfluorocarbons ( $\text{CF}_4$  and  $\text{C}_2\text{F}_6$ ) are emitted during the reduction of alumina to aluminum in the primary smelting process. The source of fluorine for  $\text{CF}_4$  and  $\text{C}_2\text{F}_6$  is the molten cryolite ( $\text{Na}_3\text{AlF}_6$ ) in which the reduction of alumina occurs. Perfluorocarbons are formed when the fluorine in cryolite reacts with the carbon in the anode (a carbon mass of paste, coke briquettes, or prebaked carbon blocks), and in the carbon lining that serves as the cathode. Although the quantities of perfluorocarbons emitted are small, these gases are significant because of their high global warming potential.

The baseline against which total GHG emissions are calculated is the zero-emissions scenario, in which no product is made. Thus, in the baseline, there are no GHG emissions in any of the following life cycle stages: raw materials acquisition, manufacturing, or MSW management.

Carbon Stocks and Carbon Sequestration Relevant to Waste: Carbon, like many other elements, cycles throughout earth's air, water, land, and biota. A carbon stock (or sink) is a point in the carbon cycle where carbon is stored. While the carbon is stored, it is not in the atmosphere contributing to the "greenhouse effect" (i.e., the trapping of heat close to the earth's surface). Examples of carbon stocks are forests, oceans, oil fields, and landfills.

"Carbon sequestration" is the opposite of GHG emissions. With carbon sequestration, carbon is removed from the carbon cycle and added to a carbon stock. For example, when a forest removes carbon from the atmosphere and converts it to wood at a faster pace than the trees are harvested (or decompose), this is known as forest carbon sequestration. Likewise, if organic matter added to a landfill does not decompose into methane or carbon dioxide, and enters into long-term storage, it is said to be "sequestered."

The baseline against which future carbon stocks are measured is the current set of carbon stocks. For the forest carbon stock, using the current stock of forest carbon as the baseline is based on an assumption that the forest will be harvested on a sustainable basis (i.e., trees will be grown at a rate at least equal to the rate at which they are cut).<sup>21</sup> Thus, we assume in the baseline that harvesting trees results in no diminution of the forest carbon stock and no additional carbon dioxide in the atmosphere. On the other hand, forest carbon sequestration increases as a result of source reduction or recycling of paper products because both source reduction and recycling cause annual tree harvests to drop below the annual growth of forests. Consequently, source reduction and recycling "get credit" for increasing the forest carbon stock, whereas other waste management options (composting, combustion, and landfilling) do not.

Landfills are another means by which carbon is removed from the atmosphere. Landfill carbon stocks increase over time because much of the organic matter placed in landfills does not decompose, especially if the landfill is located in an arid area. However, not all carbon in landfills is counted in determining the extent to which landfills are carbon stocks. For example, the analysis does not count plastic in landfills toward carbon sequestration. Plastic in a landfill represents merely a transfer from one carbon stock (the oil field containing the petroleum or natural gas from which the plastic was made) to another carbon stock (the landfill); thus, there has been no change in the overall amount of carbon stored.

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<sup>21</sup> Assuming a sustainable harvest is reasonable because the US is currently experiencing net reforestation; that is, more trees are being planted and grown than the US is consuming. This may come as a surprise to some who live in areas of the country that are being rapidly developed. However, changes in agricultural management practices, increased productivity per agricultural acre, and other factors are causing large areas of land that were once cultivated or otherwise disturbed by man to revert to forest. In addition, the average mass of wood per forested acre is increasing because, on average, forests are getting older, and the average tree is getting bigger and storing more carbon.

On the other hand, that portion of organic matter (such as yard trimmings) that does not decompose in a landfill represents an addition to a carbon stock, because it would have largely decomposed into CO<sub>2</sub> if left to deteriorate on the ground.

While changes in fossil fuel carbon stocks (i.e., reductions in oil field stores that result from the extraction and burning of oil resources) are not measured directly in this analysis, the reduction in fossil fuel carbon stocks is indirectly captured by counting the CO<sub>2</sub> emissions from fossil fuel combustion in calculating GHG emissions.

Avoided Electric Utility GHG Emissions Relevant to Waste: When a waste is used to generate electricity (either through combustion or recovery of methane from landfills), it displaces utility fossil fuels that would otherwise be consumed. Fossil fuel combustion is the single largest source of GHGs in the US. When waste is substituted for fossil fuel to generate electricity, the GHG emissions from burning the waste are offset by the avoided electric utility GHG emissions.

Baseline Year: For most parts of the analysis, we selected as the baseline year the most recent year for which data were available. For the baseline landfill methane recovery rate, however, we used values projected for the year 2000. For paper recovery, we made annual projections through 2010 that enabled us to develop an average value for the period from 1996 through 2010.<sup>22</sup> In both cases, we developed future scenarios because some of the underlying factors that affect GHG emissions are changing rapidly, and we are seeking to define relationships (e.g., between tonnage of waste landfilled and methane emissions) that represent an average over the next several years.

- In the case of landfill methane, there are three EPA programs that reduce methane emissions: one that requires landfill gas recovery at large landfills; one that promotes recovery of landfill methane on a voluntary basis at smaller landfills; and another that promotes source reduction and recycling (which results in less methane-producing waste being landfilled). In estimating the landfill methane emission reductions due to source reduction and recycling, we needed to account for the planned increase in landfill methane capture. Otherwise, EPA would be counting landfill methane emissions reductions twice: once for landfill methane capture, and once for source reduction and recycling. Because the programs to regulate landfill gas and promote voluntary methane recovery will be fully effective by 2000 (dramatically increasing methane recovery), by using a baseline year of 2000 we avoided double counting.
- For paper recovery, earlier analyses had indicated that the marginal impact of increased paper recovery on forest carbon sequestration changes over time; the impact also differs depending on the initial paper recovery rate and how that rate changes over time. To estimate the impact of increased paper recovery on forest carbon sequestration, we needed to account for these influences. First, we developed a baseline projection for paper recovery rates. We began with a projection, from the American Forest and Paper Association, that paper recovery rates will continue to increase from about 35 percent in 1994 to 50 percent by 2000. Then we developed a baseline scenario for paper recovery whose trajectory passes through 50 percent in 2000, with continued modest increases in the following years. Because we needed to estimate the effect of efforts (e.g., by EPA) to enhance recovery beyond the

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<sup>22</sup>Actually, the models we used simulated carbon sequestration through 2040, but we selected a value based on average conditions through 2010.

baseline projected rates, we developed a plausible scenario for enhanced paper recovery rates, and then compared the predicted forest carbon sequestration under the two scenarios. (Our approach is fully described in chapter 3).

## **1.5 HOW THESE INPUTS ARE TALLIED AND COMPARED**

Exhibit 1-1 shows the GHG sources and carbon sinks associated with the manufacture of various materials, and the post-consumer management of these materials as wastes. As shown in the exhibit, GHGs are emitted from: (1) the pre-consumer stages of raw materials acquisition and manufacturing; and (2) the post-consumer stage of waste management. No GHG emissions are attributed to the consumer's use of any product.

To calculate the net GHG implications of a waste management strategy for a given material, one must determine the difference between: (1) the GHG emissions associated with that material; and (2) any increases in carbon stocks and/or displaced fossil fuel combustion that offset these emissions. The formula for net GHG emissions is as follows:

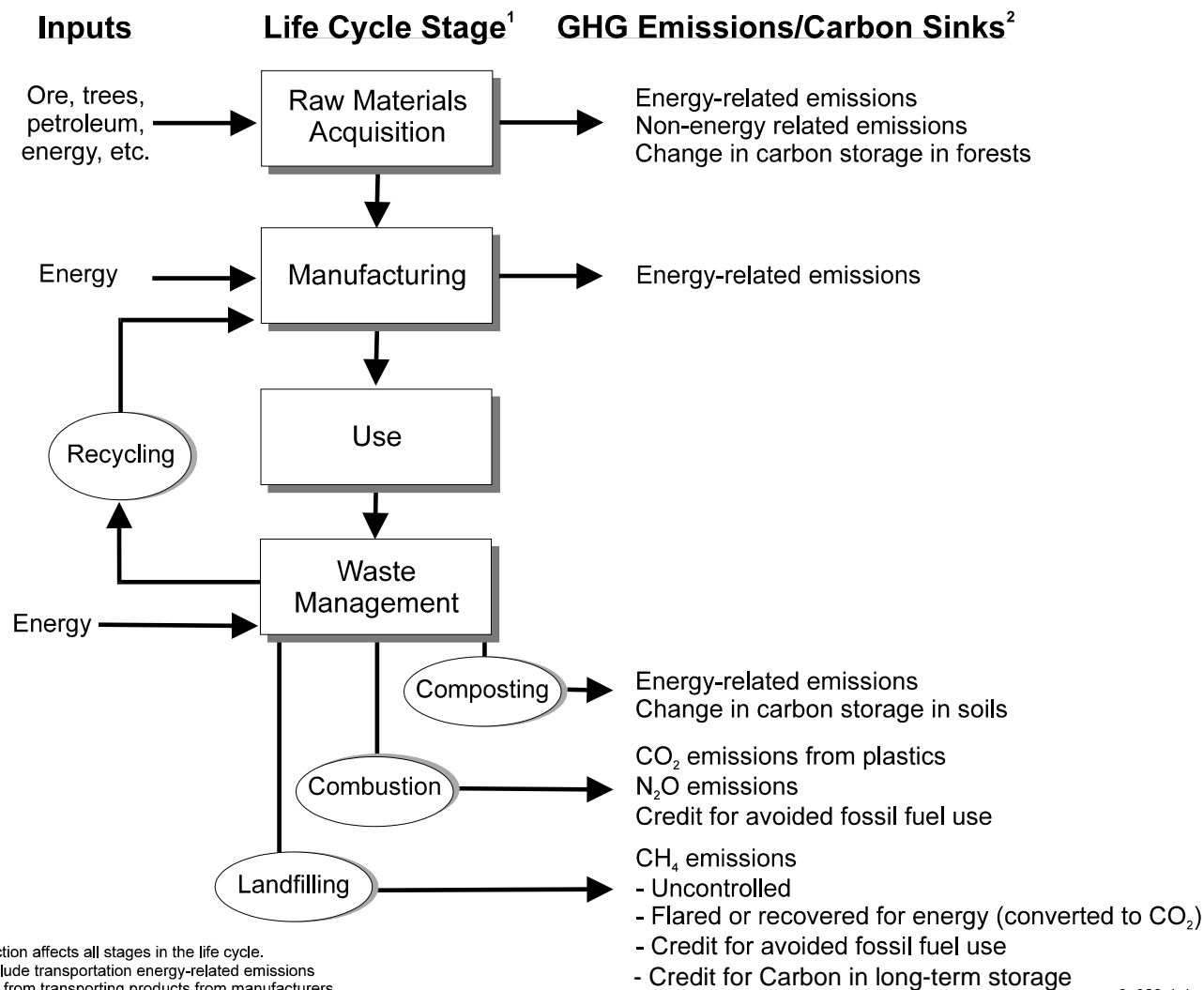
$$\text{Net GHG emissions} = \text{Gross GHG emissions} - (\text{increase in carbon stocks} + \text{avoided utility GHG emissions})$$

Comparing GHG emissions and carbon sinks for each manufacturing and waste management option with a consistent baseline allows the net GHG emissions for each option to be compared. From these comparisons, one may identify which options have the lowest net GHG emissions. For example, when a material is source reduced (i.e., some or all of it is not produced), GHG emissions throughout the life cycle are avoided. In addition, when paper products are source reduced, additional carbon is sequestered in forests.

Similarly, when a material is recycled, the GHG emissions from making an equivalent amount of material from virgin inputs are avoided. However, there are GHG emissions from making the material from recycled inputs. Generally, recycling reduces GHG emissions because, in most cases, manufacturing a product from recycled inputs requires less energy than making the product from virgin inputs, and thus reduces energy-related GHG emissions. In the case of paper, recycling also results in additional carbon sequestration in forests.

If a waste is not source reduced or recycled, it may be either composted (if it is organic matter), combusted, or landfilled. In any of these cases, the full GHG emissions associated with making the material/product are counted. These GHG emissions may be augmented by methane emissions from landfills (which themselves may be offset to some degree by energy recovery at landfills or landfill carbon sequestration). If the wastes are combusted, there may be an offset for avoided utility emissions.

## Exhibit 1-1 GHG Sources and Sinks Associated with Materials in the MSW Stream



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Exhibit 1-2 indicates how the GHG sources and sinks have been counted for each MSW management strategy to estimate net GHG emissions. For example, the top row of the exhibit shows that source reduction results in no GHG emissions or sinks (long-term carbon storage) from raw materials acquisition and manufacturing, soil carbon storage, or waste management; however, there is an increase in forest carbon sequestration.

**Exhibit 1-2**  
**Components of Net Emissions for Various Municipal Solid Waste Management Strategies**

<b>Municipal Solid Waste Management Strategy</b>	<b>Greenhouse Gas Sources and Sinks</b>			
	<b>Process and Transportation GHGs from Raw Materials Acquisition and Manufacturing</b>	<b>Change in Forest Carbon Storage</b>	<b>Change in Soil Carbon Storage</b>	<b>Waste Management GHGs</b>
Source Reduction	No emissions or sinks	Increase in forest carbon storage	No change	No emissions or sinks
Recycling	Decrease in GHG emissions due to lower energy requirements (compared to manufacture from virgin inputs) and avoided process non-energy GHGs	Increase in forest carbon storage	No change	No emissions or sinks
Composting	No emissions or sinks	No change	Increase in soil carbon storage	Compost machinery emissions, and transportation emissions
Combustion	Process and transportation emissions	No change	No change	Nonbiogenic CO <sub>2</sub> , N <sub>2</sub> O emissions, avoided utility emissions, and transportation emissions.
Landfilling	Process and transportation emissions	No change	No change	Methane emissions, long-term carbon storage in landfill, avoided utility emissions, transportation emissions, and landfill machinery emissions.

## 1.6 SUMMARY ANALYSIS OF THE LIFE CYCLE STAGES

The following sections of this chapter explain the life cycle diagram presented in Exhibit 1-1, and outline the GHG emissions and carbon sinks at each stage of the product life cycle. These GHG emissions and carbon sinks are described in detail, and quantified for each material, in chapters 2 through 7.



## **GHG Emissions and Carbon Sinks Associated With Raw Materials Acquisition and Manufacturing**

The top left of Exhibit 1-1 shows inputs for raw materials acquisition. These are virgin inputs used to make various materials including ore used to make metal products, trees used to make paper products, and petroleum or natural gas used to make plastic products. Fuel energy used to obtain or extract these material inputs is also shown.

The inputs used in manufacturing are: (1) energy, and (2) either virgin raw materials or recycled materials. In the exhibit these inputs are identified with arrows that point to the box labeled "Manufacturing."

The GHG emissions associated with raw materials acquisition and manufacturing are: (1) process energy GHG emissions, (2) transportation energy GHG emissions, and (3) process non-energy GHG emissions (for aluminum, steel, plastics, and office paper.) Each type of emission is described below. Changes in carbon storage in forests are also associated with raw materials acquisition for paper products.

This analysis assumes no GHG impacts at the raw materials acquisition and manufacturing stages for source reduction. Source reduction is assumed to entail more efficient use of a given material - for example, "lightweighting," double-sided photocopying, or extension of a product's useful life. No other material substitutions are assumed for source reduction; therefore, no corresponding increases in production and disposal of other materials are analyzed that could result in GHG emissions.<sup>23</sup>

Process Energy GHG Emissions: Process energy GHG emissions consist of CO<sub>2</sub> emissions from the combustion of fuels used in raw materials acquisition and manufacturing. CO<sub>2</sub> emissions from combustion of biomass are not counted as GHG emissions (see box on Biogenic Sources of CO<sub>2</sub> below).

The majority of process energy CO<sub>2</sub> emissions are from combustion of fuels used directly, e.g., to operate ore mining equipment or to fuel a blast furnace. Fuel is also needed to extract the oil or mine the coal that is ultimately used to produce energy; thus CO<sub>2</sub> emissions from this "pre-combustion energy" are counted in this category as well. When electricity generated by combustion of fossil fuels is used in manufacturing, the CO<sub>2</sub> emissions from the fossil fuels are also counted.

To estimate process energy GHG emissions, we first obtained estimates of both the total amount of process energy used per ton of product (measured in British thermal units or BTUs), and the fuel mix (e.g., diesel oil, natural gas, fuel oil). Next, we used emissions factors for each type of fuel to convert the amount of each type of fuel used to the GHG emissions that are produced.

In the case of recycling, we found that making a material from recycled inputs generally requires less process energy (and uses a different fuel mix) than making the material from virgin inputs.

Details of our methodology for estimating process energy GHG emissions is provided in Chapter 2.

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<sup>23</sup> Although material substitution is not considered here, it remains a high priority issue for future EPA research.

## CO<sub>2</sub> Emissions from Biogenic Sources

The US and all other parties to the Framework Convention on Climate Change agreed to develop inventories of GHGs for purposes of (1) developing mitigation strategies and (2) monitoring the progress of those strategies. The Intergovernmental Panel on Climate Change (IPCC) developed a set of inventory methods to be used as the international standard. (IPCC, *IPCC Guidelines for National Greenhouse Gas Inventories* (three volumes), no date.) In selecting the methodologies used in this report to evaluate emissions and sinks of GHGs, we attempted to be consistent with IPCC's guidance.

One of the elements of the IPCC guidance that deserves special mention is the approach used to address CO<sub>2</sub> emissions from biogenic sources. For many countries, the treatment of CO<sub>2</sub> releases from biogenic sources is most important when addressing releases from energy derived from biomass (e.g., burning wood), but this element is also important when evaluating waste management emissions (for example, the decomposition or combustion of grass clippings or paper). The carbon in paper and grass trimmings was originally removed from the atmosphere by photosynthesis, and under natural conditions, it would eventually cycle back to the atmosphere as CO<sub>2</sub> due to degradation processes. The quantity of carbon that these natural processes cycle through the earth's atmosphere, waters, soils, and biota is much greater than the quantity added by anthropogenic GHG sources. But the focus of the Framework Convention on Climate Change is on anthropogenic emissions - emissions resulting from human activities and subject to human control - because it is these emissions that have the potential to alter the climate by disrupting the natural balances in carbon's biogeochemical cycle, and altering the atmosphere's heat-trapping ability.

Thus, for processes with CO<sub>2</sub> emissions, if (a) the emissions are from biogenic materials and (b) the materials are grown on a sustainable basis, then those emissions are considered to simply close the loop in the natural carbon cycle, that is they return to the atmosphere CO<sub>2</sub> that was originally removed by photosynthesis. In this case, the CO<sub>2</sub> emissions *are not* counted. (For purposes of this analysis, biogenic materials are paper, yard trimmings, and food scraps.) On the other hand, CO<sub>2</sub> emissions from burning fossil fuels *are* counted because these emissions would not enter the cycle were it not for human activity. Likewise, CH<sub>4</sub> emissions from landfills *are* counted - even though the source of carbon is primarily biogenic, CH<sub>4</sub> would not be emitted were it not for the human activity of landfilling the waste, which creates anaerobic conditions conducive to CH<sub>4</sub> formation.

Note that this approach does not distinguish between the timing of CO<sub>2</sub> emissions, provided that they occur in a reasonably short time scale relative to the speed of the processes that affect global climate change - as long as the biogenic carbon would eventually be released as CO<sub>2</sub>, it does not matter whether it is released virtually instantaneously (e.g., from combustion) or over a period of a few decades (e.g., decomposition on the forest floor).

Transportation Energy GHG Emissions: Transportation energy GHG emissions consist of CO<sub>2</sub> emissions from the combustion of fuels used to transport raw materials and intermediate products to the final manufacturing or fabrication facility. We based our estimates of transportation energy GHG emissions on: 1) the amounts of raw material inputs and intermediate products used in manufacturing one ton of each material; 2) the average distance that each raw material input or intermediate product is transported; and 3) the transportation modes and fuels used. For the amounts of fuel used, we used data on the average fuel consumption per ton-mile for each mode of transportation. Then we used an emission factor for each type of fuel to convert the amount of each type of fuel consumed, to the GHG emissions produced.

More detail on our methodology to estimate transportation energy GHG emissions is provided in Chapter 2.

Process Non-Energy GHG Emissions: Some GHG emissions occur directly in the manufacture of certain materials and are not associated with energy consumption. In this analysis, we refer to these emissions as process non-energy emissions. For example, the production of steel or aluminum requires lime (calcium oxide, or CaO), which is produced from limestone (calcium carbonate, or CaCO<sub>3</sub>); the manufacture of lime results in CO<sub>2</sub> emissions. Other process non-energy GHG emissions are associated with production of plastics, office paper, and tissue paper. In some cases, process non-energy GHG emissions are only associated with production using virgin inputs; in other cases, these emissions result when either virgin or recycled inputs are used. These emissions are described in Chapter 2.

Carbon Sinks: The only carbon sink in the stages of raw materials acquisition and manufacturing is the additional carbon sequestration in trees associated with source reduction or recycling of paper products. Our methodology for estimating forest carbon sequestration is described in Chapter 3.

### **GHG Emissions and Carbon Sinks Associated With Waste Management**

As shown at the bottom of Exhibit 1-1, there are, depending on the material, up to four waste management options once a material is manufactured: recycling, composting, combustion, and landfilling. This section describes the GHG emissions and carbon sinks associated with these four waste management options.

In this analysis, source reduction is measured by the amount of material that would otherwise be produced but is not being produced because of a program promoting source reduction. Thus, with source reduction there are no emissions from MSW management.

Recycling: When a material is recycled, it is used in place of virgin inputs in the manufacturing process. Thus, the only GHG emission consequences are those from manufacturing a material from recycled rather than virgin inputs (including transportation GHGs and avoided GHGs from raw materials acquisition); there are no GHG emissions at the MSW management stage. (If the product made from the recycled material is later composted, combusted, or landfilled, the GHG emissions at that point would be attributed to the product that was made from the recycled material.) Chapter 4 details GHG emissions from recycling.

Most of the materials considered in this analysis are modeled as being recycled in a "closed loop" (e.g., newspapers are recycled into new newspapers). However, office paper and corrugated boxes are modeled as being recycled in an "open loop" (i.e., they are recycled into more than one product):

- Office paper is modeled as being recycled into either office paper or tissue paper; and
- Corrugated boxes are modeled as being recycled into either corrugated boxes or folding boxes.

By developing GHG estimates for the manufacture of all four of these products, we were able to estimate the GHG implications of "open loop" recycling of office paper and corrugated boxes. We recognize that other materials are recycled in open loop processes, but due to limited resources, we could not analyze all open loop processes.

Composting: When organic materials are composted, most of their organic mass quickly decomposes to CO<sub>2</sub>. The materials that may be composted (e.g., leaves, brush, grass, food waste, newspapers) are all originally produced by trees or other plants. As described in the text box above, the CO<sub>2</sub> emitted from these materials during composting is biogenic CO<sub>2</sub>, and thus is not counted in GHG emissions.

There is some potential for the composting of yard trimmings to result in production of more humic material (natural organic polymers, which degrade at a slow rate) than is produced when yard trimmings are left to decompose in the yard. This process may act to enhance long-term carbon storage in soils to which compost is applied.

Although composting may result in some production of methane (due to anaerobic decomposition in the center of the compost pile) compost researchers concluded that the methane is almost always oxidized to CO<sub>2</sub> before it escapes from the compost pile.

Because the CO<sub>2</sub> emissions from composting are biogenic, and there are generally no methane emissions, the only GHG emissions from composting result from transportation of compostable materials to composting facilities, and mechanical turning of the compost piles. Carbon cycling in compost operations is discussed in Chapter 5.

Combustion: When waste is combusted, two GHGs are emitted: CO<sub>2</sub> and N<sub>2</sub>O. Non-biogenic CO<sub>2</sub> emitted during combustion (i.e., CO<sub>2</sub> from plastics) is counted toward the GHG emissions associated with combustion, but biogenic CO<sub>2</sub> is not. Because most waste combustors produce electricity that substitutes for utility-generated electricity, the net GHG emissions are calculated by subtracting the utility GHG emissions avoided from the gross GHG emissions. GHG emissions from combustion are described in Chapter 6.

Landfilling: When organic matter is landfilled, some of this matter decomposes anaerobically and releases methane, a potent GHG. Some of the organic matter never decomposes at all; instead it becomes sequestered carbon. (Landfilling of metals and plastics does not result in either methane emissions or carbon sequestration).

At some landfills, virtually all of the methane produced is released to the atmosphere. The gross GHG emissions from these landfills consist of the methane emissions. At other landfills, methane is captured for flaring or combustion with energy recovery (i.e., electricity production). Most of the captured methane is converted to CO<sub>2</sub>, which is not counted as a GHG because it is biogenic. With combustion of methane for energy recovery, credit is given for the electric utility GHG emissions avoided. Regardless of the fate of methane, credit is given for the landfill carbon sequestration associated with landfilling of some organic materials. GHG emissions and carbon sinks from landfilling are described in Chapter 7.